

CLAIMS

1. Apparatus for enhancing vision of a user having an eye that includes a retina, the apparatus comprising:

5 a focal modulation device, which is adapted to focus light from objects in a field of view of the user onto the retina while alternating between at least first and second focal states that are characterized by different, respective first and second focal depths, at a rate in excess of a flicker-fusion frequency of the user.

2. The apparatus according to claim 1, wherein in the first focal state, the focal modulation device is operative to focus the light from distant objects onto the retina, and in the
10 second focal state, the focal modulation device is operative to focus the light from near objects onto the retina.

3. The apparatus according to claim 1 or 2, and comprising a lens body, comprising a transparent optical material having a predetermined refractive power, wherein the focal modulation device is adapted to modulate the refractive power of the lens body.

15 4. The apparatus according to claim 3, wherein the focal modulation device is encapsulated in the lens body.

5. The apparatus according to claim 4, wherein the lens body is adapted to serve as a contact lens on a surface of the eye.

6. The apparatus according to claim 4, wherein the lens body is adapted to be implanted
20 as an intraocular lens within the eye.

7. The apparatus according to claim 3, wherein the lens body is adapted to serve as a spectacle lens.

8. The apparatus according to claim 1 or 2, wherein the focal modulation device comprises:

25 a spatial light modulator (SLM), which is adapted to focus the light; and
a control circuit, which is coupled to actuate the SLM so as to alternate between the first and second focal states.

9. The apparatus according to claim 1 or 2, wherein the focal modulation device is adapted to alternate between the first and second focal states and a third focal state, which is characterized by a third focal depth, intermediate the first and second focal depths.

10. The apparatus according to claim 1 or 2, wherein the focal modulation device is adapted to alternate between the at least first and second focal states with a period of alternation between 12 ms and 30 ms.

11. A lens, comprising:

a lens body, comprising a transparent optical material having a predetermined refractive power; and

10 a focal modulation device fixed to the lens body and comprising:

a semiconductor substrate;

a spatial light modulator (SLM) formed on the substrate so as to permit light collected by the lens body to pass through the SLM;

15 a control circuit, which is formed on the substrate and is coupled to actuate the SLM so as to modulate the refractive power that is applied to the light passing through the SLM; and

a photovoltaic cell, which is formed on the substrate and is coupled to provide electrical power to the control circuit responsively to light that is incident on the photovoltaic cell.

20 12. The lens according to claim 11, wherein the focal modulation device is encapsulated within the lens body.

13. The lens according to claim 11, wherein the control circuit is adapted to actuate the SLM so as to cause the lens to alternate between at least first and second focal states that are characterized by different, respective first and second focal depths, at a rate in excess of a flicker-fusion frequency of a user of the multifocal lens.

25 14. The lens according to claim 13, wherein the focal modulation device comprises an oscillator, which is coupled to provide a clock signal to the control circuit, and wherein the control circuit is adapted to determine the rate of alternation between the first and second focal states responsively to the clock signal.

15. The lens according to claim 14, wherein the control circuit is adapted to determine the rate of alternation between the first and second focal states independently of any signal generated externally to the lens.

16. The lens according to any of claims 11-15, wherein the lens body is adapted to serve as a contact lens on a surface of an eye of a user.

17. The lens according to any of claims 11-15, wherein the lens body is adapted to be implanted as an intraocular lens within an eye of a user.

18. The lens according to any of claims 11-15, wherein the lens body is adapted to serve as a spectacle lens.

19. The lens according to any of claims 11-15, wherein the SLM comprises a matrix of liquid crystal elements.

20. The lens according to claim 19, wherein the matrix of liquid crystal elements comprises:

an insulating layer deposited on the substrate and having recesses formed therein so as to define the matrix;

a liquid crystal material contained within the recesses; and

a polymer layer formed over the recesses so as to hold the liquid crystal material within the recesses.

21. The lens according to claim 20, wherein the focal modulation device comprises a plurality of conductors formed on the substrate so as to couple the control circuit to the liquid crystal elements, and wherein the polymer layer comprises a conductive material which is coupled to provide a common ground contact for the matrix of the liquid crystal elements.

22. An electronic device, comprising:

a semiconductor substrate;

an insulating layer formed on the substrate and having a matrix of recesses formed therein;

a non-solid material contained within the recesses;

a plurality of conductors, formed on the substrate and in communication with the recesses, so as to perform at least one of conveying electrical input signals to the non-solid material and receiving electrical output signals from the non-solid material; and

a polymer layer formed over the recesses so as to hold the non-solid material within the recesses.

23. The device according to claim 22, wherein the non-solid material comprises a liquid crystal material.

5 24. The device according to claim 23, and comprising a control circuit, which is formed on the substrate and is coupled to convey the electrical input signals through the conductors to the liquid crystal material in the recesses so as to spatially modulate light passing through the device.

10 25. The device according to any of claims 22-24, wherein the polymer layer comprises a conductive material which is coupled to provide a common ground contact for the non-solid material within the recesses.

15 26. The device according to any of claims 22-24, wherein the semiconductor substrate comprises a first side, on which the insulating layer and conductors are formed, and a second side, and wherein the second side is thinned so as to permit light to be incident on the non-solid material via the second side.

27. The device according to claim 26, and comprising a transparent layer formed on the substrate below the matrix of recesses in the insulating layer, wherein the second side of the substrate is thinned so as to expose the transparent layer.

20 28. A method for enhancing vision of a user having an eye that includes a retina, the method comprising focusing light from objects in a field of view of the user onto the retina in alternation between at least first and second focal states that are characterized by different, respective first and second focal depths, at a rate of alternation that is in excess of a flicker-fusion frequency of the user.

25 29. The method according to claim 28, wherein focusing the light comprises, in the first focal state, focusing the light from distant objects onto the retina, and in the second focal state, focusing the light from near objects onto the retina.

30. The method according to claim 28 or 29, wherein focusing the light comprises placing a lens having a predetermined refractive power between the eye and the field of view, modulating the refractive power of the lens at the rate of alternation.

31. The method according to claim 30, wherein the lens comprises a lens body, and wherein modulating the refractive power comprises applying electrical signals to an optoelectronic focal modulation device that is encapsulated in the lens body.

32. The method according to claim 31, wherein placing the lens comprises placing the lens body so as to contact a surface of the eye.

33. The method according to claim 31, wherein placing the lens comprises implanting the lens body within the eye.

34. The method according to claim 31, wherein modulating the refractive power comprises generating the electrical signal at the rate of alternation independently of any signal generated externally to the lens.

35. The method according to claim 28 or 29, wherein focusing the light comprises mounting a focal modulation device on a spectacle frame, which is worn by the user, and switching the focal modulation device between the first and second focal states.

36. The method according to claim 28 or 29, wherein focusing the light comprises placing a spatial light modulator (SLM) between the eye and the field of view, and actuating the SLM so as to alternate between the first and second focal states.

37. The method according to claim 28 or 29, wherein focusing the light comprises alternating between the first and second focal states and a third focal state, which is characterized by a third focal depth, intermediate the first and second focal depths.

38. The method according to claim 28 or 29, wherein focusing the light comprises alternating between the at least first and second focal states with a period of alternation between 12 ms and 30 ms.

39. A method for producing a lens, comprising:

forming a spatial light modulator (SLM) on a semiconductor substrate;

forming a control circuit on the substrate, so that the control circuit is coupled to actuate the SLM;

forming a photovoltaic cell on the substrate, so that the photovoltaic cell is coupled to provide electrical power to the control circuit responsively to light that is incident on the photovoltaic cell.

40. The method according to claim 39, wherein the control circuit is configured to actuate the SLM so as to cause the lens to alternate between first and second focal states that are characterized by different, respective first and second focal depths, at a rate in excess of a flicker-fusion frequency of a user of the lens.

5 41. The method according to claim 40, and comprising forming an oscillator on the substrate, wherein the oscillator is coupled to provide a clock signal to the control circuit, and wherein the control circuit is configured to determine the rate of alternation between the first and second focal states responsively to the clock signal.

10 42. The method according to claim 41, wherein the control circuit is configured to determine the rate of alternation between the first and second focal states independently of any signal generated externally to the lens.

15 43. The method according to any of claims 39-42, and comprising fixing the substrate, on which the SLM, control circuit and photovoltaic cell are formed, to a lens body comprising a transparent optical material so as to permit light collected by the lens body to pass through the SLM.

44. The method according to claim 43, wherein fixing the substrate comprises encapsulating the substrate in the lens body.

20 45. The method according to claim 43, wherein the lens body has a predetermined refractive power, and wherein forming the control circuit comprises configuring the control circuit to actuate the SLM so as to modulate the refractive power that is applied to the light passing through the SLM.

46. The method according to claim 43, wherein fixing the substrate comprises producing the lens body so as to serve as a contact lens on a surface of an eye of a user.

25 47. The method according to claim 43, wherein fixing the substrate comprises producing the lens body so as to be implanted as an intraocular lens within an eye of a user.

48. The method according to claim 43, wherein fixing the substrate comprises producing the lens body so as to serve as a spectacle lens.

49. The method according to any of claims 39-42, wherein forming the SLM comprises forming a matrix of liquid crystal elements on the substrate.

50. The method according to claim 49, wherein forming the matrix of liquid crystal elements comprises:

depositing an insulating layer on the substrate, the insulating layer having recesses formed therein so as to define the matrix;

5 inserting a liquid crystal material into the recesses; and

forming a polymer layer over the recesses so as to hold the liquid crystal material within the recesses.

51. The method according to claim 50, and comprising forming a plurality of conductors on the substrate so as to couple the control circuit to the liquid crystal elements, and wherein
10 forming the polymer layer comprises forming a conductive layer over the liquid crystal material so as to provide a common ground contact for the matrix of the liquid crystal elements.

52. A method for producing an electronic device, comprising:

15 depositing an insulating layer on a semiconductor substrate, the insulating layer having a matrix of recesses formed therein;

filling the recesses with a non-solid material;

forming a plurality of conductors on the substrate in communication with the recesses, so as to perform at least one of conveying electrical input signals to the non-solid material and receiving electrical output signals from the non-solid material; and

20 forming a polymer layer over the recesses so as to hold the non-solid material within the recesses.

53. The method according to claim 52, wherein the non-solid material comprises a liquid crystal material.

54. The method according to claim 53, and comprising forming a control circuit on the
25 substrate, wherein the control circuit is coupled to convey the electrical input signals through the conductors to the liquid crystal material in the recesses so as to spatially modulate light passing through the device.

55. The method according to any of claims 52-54, wherein the polymer layer comprises a conductive material which is coupled to provide a common ground contact for the non-solid
30 material within the recesses.

56. The method according to any of claims 52-54, wherein the semiconductor substrate comprises a first side, on which the insulating layer and conductors are formed, and a second side, and comprising thinning the second side so as to permit light to be incident on the non-solid material via the second side.

5 57. The method according to claim 56, and comprising forming a transparent layer on the substrate below the matrix of recesses in the insulating layer, wherein thinning the second side comprises exposing the transparent layer.

58. A focal modulation device, comprising:

a semiconductor substrate;

10 a spatial light modulator (SLM) formed on the substrate so as to permit light to pass through the SLM;

a control circuit, which is formed on the substrate and is coupled to actuate the SLM so as to modulate the refractive power that is applied to the light passing through the SLM; and

15 a photovoltaic cell, which is formed on the substrate and is coupled to provide electrical power to the control circuit responsively to light that is incident on the photovoltaic cell.

59. The device according to claim 58, wherein the control circuit is adapted to actuate the SLM so as to alternate between at least first and second focal states that are characterized by different, respective first and second focal depths, at a rate in excess of a flicker-fusion
20 frequency of a user of the device.

60. The device according to claim 59, and comprising an oscillator, which is coupled to provide a clock signal to the control circuit, wherein the control circuit is adapted to determine the rate of alternation between the first and second focal states responsively to the clock signal.

61. The lens according to claim 60, wherein the control circuit is adapted to determine the
25 rate of alternation between the first and second focal states independently of any signal generated externally to the device.

62. The device according to any of claims 58-61, wherein the SLM comprises a matrix of liquid crystal elements.

63. The device according to claim 62, wherein the matrix of liquid crystal elements
30 comprises:

an insulating layer deposited on the substrate and having recesses formed therein so as to define the matrix;

a liquid crystal material contained within the recesses; and

5 a polymer layer formed over the recesses so as to hold the liquid crystal material within the recesses.

64. The device according to claim 63, and comprising a plurality of conductors formed on the substrate so as to couple the control circuit to the liquid crystal elements, wherein the polymer layer comprises a conductive material which is coupled to provide a common ground contact for the matrix of the liquid crystal elements.